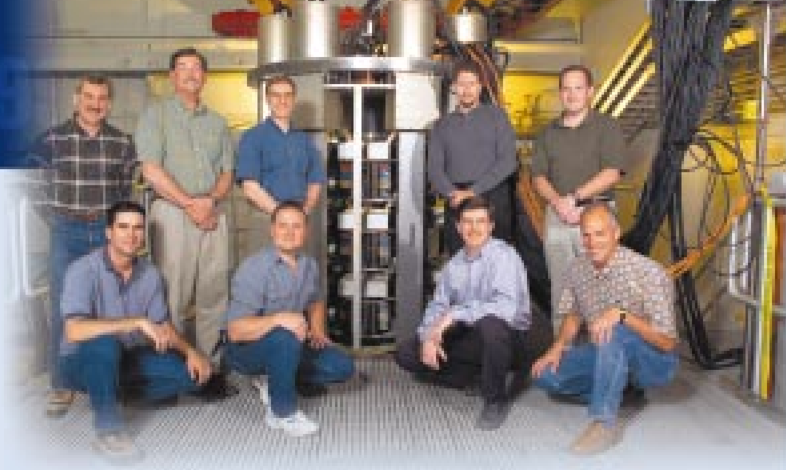
Breakthrough Design for Accelerators



The development team poses with their Advanced Radiographic Machine (ARM) modulator. Kneeling, from left to right, are Brad Hickman, Bryan Lee, Craig Brooksby, and Steve Hawkins. Standing are Hugh Kirbie, Craig Ollis, George Caporaso, Roy Hanks, and Rob Saethre.

LIKE many tools of high-energy physics, linear induction accelerators have been improving in small steps over the past several decades. Now a breakthrough design for the accelerator power source has advanced their capabilities immensely. The new design, based for the first time on solid-state components, promises important progress for the Department of Energy's Stockpile Stewardship Program as well as imaginative new uses for accelerators, ranging from waste treatment to space exploration.

The new accelerator power source, called the Advanced Radiographic Machine (ARM) modulator, is the product of a six-year development effort by a team of researchers from Lawrence Livermore and Bechtel Nevada Corporation. The technology enables linear induction accelerators, which typically generate thousand-ampere electron-beam currents at high energies, to fire at up to 2 megahertz (millions of times per second)—a rate some 400 times greater than that of current machines.

A prototype ARM modulator built at Livermore reliably delivers a burst of 45-kilovolt, 4.8-kiloampere pulses that can be varied in length from 200 nanoseconds (billionths of a second) to 2 microseconds (millionths of a second). Its solid-state components permit high recovery rates and are easy to cool, thereby ensuring enormous high-average-power levels.

In addition to performance increases, the solid-state technology provides an unprecedented degree of control over the voltage waveform at each stage of the accelerator, thereby permitting unparalleled flexibility in shaping pulses. The machine also generates pulses in a single-step operation, a feature that differs from conventional technology and contributes to substantial cost savings.

Technology Has a Kicker

The ARM modulator can also power so-called kicker technology, in which an electron beam is divided in half, then half again, to result in four beams, each one-fourth the duration of the original pulse, that are sent down separate pathways. In this way, the ARM technology permits a single accelerator to perform as if it were four—or more—accelerators operating in parallel, thereby achieving dramatic cost savings and contributing to a high level of control and flexibility.

The ARM modulator was developed as part of DOE's Stockpile Stewardship Program to ensure the performance, reliability, and safety of the U.S. nuclear weapons stockpile without the use of nuclear testing. One important part of the program is the use of pulsed radiographs to examine the complex chemical explosive phase of a stockpiled weapon. For these experiments, the weapon's nuclear components are replaced with surrogate materials.

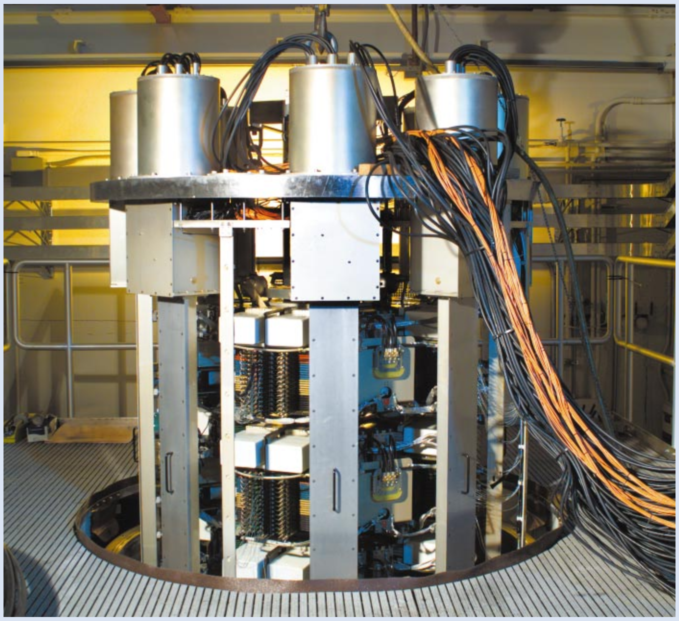
Current DOE linear-induction accelerators, such as Livermore's Flash X-Ray Facility, produce radiographs of exploding warheads from a single, 60-nanosecond pulse of electrons. The beam of electrons typically is focused through a lens down to 1 millimeter in diameter to strike a target, usually tantalum or tungsten, and in the process emits x rays. In each case, the explosive action is imaged for only one moment in time, much like a routine medical x ray.

A single image taken from one vantage point does not provide much data. Weapons scientists need a facility that can produce several consecutive bursts of x rays to image the explosive motion at several moments in time. Ideally, these bursts would examine the explosions from different vantage points to give a three-dimensional assessment of the event, similar to a computed tomography (CT) scan.

Power Modulators at the Heart

Six years ago, a Livermore–Bechtel Nevada team led by Livermore electrical engineer Hugh Kirbie took on the challenge of developing new technology to image imploding warheads over time and from multiple axes. The resulting design is based on power modulators that integrate energy storage, high-speed solid-state electronics, and a hybrid form of transformer, all into one compact package. The modulators can be stacked like flashlight batteries to achieve high voltage and power—to 50-megawatt pulses per modulator and higher.

Even though modern solid-state devices are unmatched in speed, precision, long life, reliability, and cost, their use in the ARM technology is the most radical aspect of its design.



The Advanced Radiographic Machine (ARM) power source, consisting of three stacked solid-state modulators.

Traditionally, it has been difficult to use transistors for high-voltage, pulsed-power systems; they are susceptible to large voltage and current spikes. However, the team overcame those problems with a robust design based on newly available metal-oxide-semiconductor field-effect transistors (MOSFETs).

As testimony to the exhilarating pace of solid-state component development, the original MOSFETs already can be replaced by integrated gate bipolar transistors, which are presently used in bullet trains. The use of these new devices reduces the total parts count drastically and further lowers ARM's overall cost.

The ARM technology will be used to power the kicker system of the Dual-Axis Radiographic Hydrotest Facility (DARHT), now under construction at Los Alamos National Laboratory. The kicker system will create four approximately 50-nanosecond pulses from a 2-microsecond pulse to enable four stop-action radiographs from two axes for every experiment. Although not truly three dimensional, the images will be far more informative than any similar radiograph produced to date. For the first time, researchers will obtain time-resolved information, including shapes, densities, and chemical explosive material distribution within the detonating warhead.

Valuable and Varied Uses

In a related project, team members will investigate using the ARM modulator technology to power an accelerator testbed to study DARHT x-ray targets. When an electron beam strikes a metal target to generate x rays, it blows a hole through the target. Facilities such as DARHT, with their multiple bursts of x rays, will ultimately require a system to provide fresh targets rapidly.

The ARM technology can easily be adapted to a number of other important research and development applications because of the power source's combination of unprecedented high pulse-repetition rates, reliability, and beam control. The team is investigating the technology as a driver for heavy-ion fusion to replace large laser systems now in use. A commercial fusion reactor would require a power source such as ARM that can operate at several hundred kilohertz.

The team is also collaborating with Stanford Linear Accelerator Center scientists to develop an all-solid-state power source for the Next Linear Collider, now under study as the follow-on to current high-energy physics experiments worldwide. Lawrence Livermore is one of the principal partners in planning this international facility that will study exotic new elementary particles.

For a more day-to-day application, the ARM can be used as a high-voltage power source for cleaning exhaust gases in flues. Other applications include large-scale radiation processing of food products, sterilization of medical equipment, transmutation of atomic waste, and strengthening of materials and tools by firing selected ions into their crystalline structures.

An intriguing possibility is using the technology to convert electron-beam power into laser light via free-electron lasers. In this application, the intense light could be used to power a space station, destroy hostile missiles or aircraft, or propel space vehicles.

The team believes that commercial ARM modulator units for myriad applications could be produced at substantially reduced prices through large production runs. In addition, there is every indication that the power-handling capacity of larger solid-state devices will continue to expand while their costs continue their steep decline. Clearly, linear induction accelerators powered by ARM technology face a bright future.

—Arnie Heller

Key Words: Advanced Radiographic Machine (ARM), Bechtel Nevada Corporation, integrated gate bipolar transistors, metal-oxide-semiconductor field-effect transistor (MOSFET), Next Linear Collider, Stanford Linear Accelerator Center.

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